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Proton radiation effects on optical constants of Al film reflector*

Liu Hai(刘 海), Wei Qiang(魏 强)†,
He Shi-Yu(何世禹), and Zhao Dan(赵 丹)

Space Materials and Environment Engineering Laboratory, Harbin Institute of Technology, Harbin 150001, China

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The Al film reflectors can yield a high-reflectance over a broad wavelength region, and have been widely used in the spacecraft optical instruments for high quality optical applications. Under the irradiation of charged particles in the Earth radiation belt, the reflectors could be deteriorated. In order to reveal the deterioration mechanism, the change in optical constants of Al film reflector induced by proton radiation with 60 keV was studied in an environment of vacuum with heat sink. Experimental results showed that when the radiation damage primarily occurs in the Al reflecting film, the extinction coefficient k will gradually decrease with increasing radiation fluence, which results in the decrease of the energies of reflective light. Therefore, the proton radiation induced an obvious degradation of spectral reflectance in the wavelength region from 200 to 800 nm on the Al film reflector.

Keywords: Al film reflector, optical constants, radiation damage
PACC: 7820D, 8750G, 6180

1. Introduction

Aluminium film has been used for a long time as broad band front reflecting surfaces on high-quality optics used in spacecrafts.[1,2] However, a property degradation of optical components or materials will occur for spacecrafts in space environment. It is shown that atomic oxygen exposure and thermal effects of substrate materials could be primarily responsible for the property degradation of the Al films.[3,4] Few studies are related to the space radiation effects on optical film units. The discovery of Van Allen radiation belts in the early 1960s drew much attention of the spacecraft designers.[5] Previous work[6,7] showed that optical thin film units, such as optical reflectors, would be subjected to the damage of charged particles in the space radiation belts, especially the low-energy protons. The flux of the charged particles increases while decreasing their energy in the Van Allen radiation belts which consist principally of protons and electrons, and the protons with energies below 200 keV have large fluxes up to 10^8 particles/($cm^2 \cdot s$).[8] Generally, the lower the particle energy, the relatively shorter the penetration depth of the particles into materials. Therefore, the energy absorbed by the materials is mainly concentrated on the surface layers. Consequently, the effects of proton radiation with lower energies on optical materials are important, especially for long lifetime spacecrafts.

We present here an investigation of damage effects on Al film reflectors induced by radiation of protons with 60 keV in an environment of vacuum with heat sink. The changes in reflectance and optical constants of the reflectors before and after proton irradiation are measured and calculated to describe the radiation effects.

2. Experiments

Figure 1 shows the structure of the samples used in the experiment, consisting of the JGS1 quartz glass substrate with a thickness of 2 mm, a 500 nm thick Al reflecting layer and a 100 nm thick protection layer of SiO_2. The Al layer was deposited in vacuum using the electron beam and deposition technique. The purity of Al and SiO_2 was respectively 99.99% and 99.999%. The physical property parameters of Al, SiO_2 films and JGS1 quartz glass are found in Ref.[9].

*Project supported by the National Key Basic Research Special Foundation of China (G19990650).
†E-mail: sinowq@yahoo.com.cn

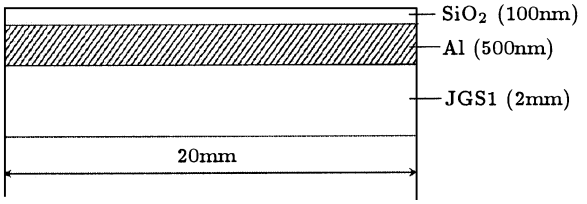


Fig.1. Schematic of Al film reflector samples.

The irradiation experiment was conducted using a proton accelerator with energy up to 200 keV. The vacuum in the test chamber was 10^{-4} Pa and there was a liquid nitrogen screen to provide a 77 K heat sink. The energy of protons was chosen to be 60 keV. The proton flux was $1.25\times10^{12}\,\mathrm{cm^{-2}\cdot s^{-1}}$ and the irradiation fluence was up to $1\times10^{16}\,\mathrm{cm^{-2}}$. The proton flux was perpendicular to the reflective surface of samples. The energy of 60 keV is selected in order to set the maximum concentration level in the Al film by SRIM[10] simulation.

Changes in reflectance of the samples before and after proton irradiation were examined using a Perkin–Elmer spectrometer type Lambda 950. The optical constants of Al reflectors before and after irradiation were determined using Kramers–Kroning relationship (K–K relationship) and Drude's theory.

3. Results and discussion

3.1. Changes in spectral reflectance

Figure 2 shows the reflective spectra of the sample before and after proton irradiation as a function of fluence in wavelengths ranging from 200 to 2200 nm. Before irradiation, the spectral reflectance in the wavelength region from 250 to 700 nm reached approximately 90%, and had a minimum of 87% at 810 nm. In the near-infrared region larger than 980 nm, the spectral reflectance was all higher than 90%. It indicated that the original samples possessed a superior reflective property. Once protons-irradiated, the spectral reflectance appeared to change in the wavelength region from 200 to 600 nm. With further increasing fluence, the effect gradually spread towards the higher wavelength, but little influence was observed in the infrared region. When radiation fluence reached $1\times10^{16}\,\mathrm{cm^{-2}}$, the spectral reflectance decreased obviously in the wavelength region from 200–800 nm.

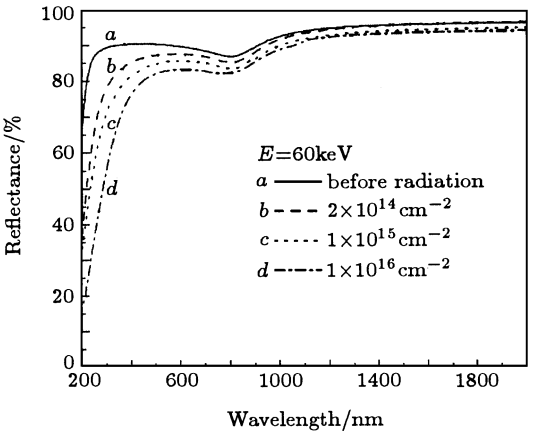


Fig.2. Specular reflectance for Al film reflector before and after proton irradiation with 60 keV.

3.2. Damage distribution

From the above experimental results, it is clear that the radiation damage on optical reflectors is an important problem. Figure 3 presents a SRIM simulation of proton distribution. The simulation results show that there is a peak concentration of protons in the Al film of samples. This demonstrates that more energy would be absorbed in the Al film. Generally, in the case of light ions such as protons, the damage and implanted profiles will correspond to each other closely in depth. Therefore, there are many radiation-induced damages in films of reflectors.

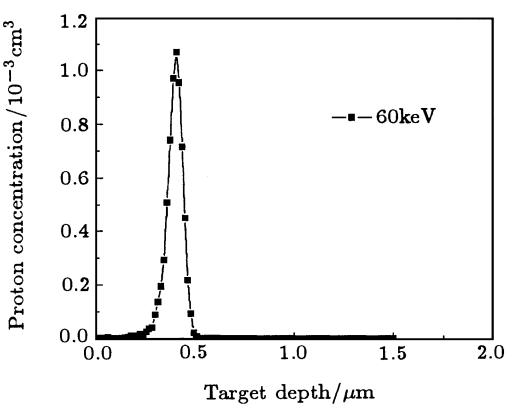


Fig.3. Concentration distribution of proton radiation with 60 keV energy in Al film reflector.

3.3. Change in optical constants

Generally, optical constant reflects microcosmic structure of electronic state in the interior of solid materials and different microphysics processes under different physical conditions.[11–14] Therefore, the radiation effects of the Al film reflectors are also characterized by the variations in refractive index n and extinction coefficient k with radiation fluence. The

optical constants of reflecting film of the reflectors are calculated from the measured reflective spectrum in terms of the K–K relationship. In the experiment, the reflecting film is so thick that the influence of substrate can be ignored. When the incident light is perpendicular to the surface of reflectors, the reflectance is given by

$$R = [(n-1)^2 + k^2]/[(n+1)^2 + k^2], \qquad (1)$$

where n and k are the refractive index and extinction coefficient of reflective films respectively. R is given by the measured spectral reflectance.

According to K–K dispersive relation, the following relationships can be given:

$$\theta(\omega) = -\frac{\omega}{\pi} P \int_0^\infty \frac{2\ln|r(\omega')|}{\omega'^2 - \omega^2} \mathrm{d}\omega'$$

$$= -\frac{\omega}{\pi} P \int_0^\infty \frac{\ln R(\omega')}{\omega'^2 - \omega^2} \mathrm{d}\omega', \qquad (2)$$

where θ is the phase shift on reflection, P is the principal value of the Cauchy integral formula. By part integral, we obtain:

$$\theta(\omega) = \frac{1}{2\pi} \int_0^\infty \ln\left|\frac{\omega' - \omega}{\omega' + \omega}\right| \frac{d\ln R(\omega')}{\mathrm{d}\omega'} \mathrm{d}\omega'. \qquad (3)$$

However, the measurement of reflective specula is impossible for the integral range of 0 to ∞. In fact, when $\omega >> \omega'$ and $\omega << \omega'$, $\ln\left|\frac{\omega' - \omega}{\omega' + \omega}\right|$ approaches zero. Therefore, the integral expression (3) and the phase shift θ can be approximately solved in a finite wavelength range. Finally, the optical constants are calculated by the following equations:

$$k = -2\sqrt{R}\sin\theta/(1 + R - 2\sqrt{R}\cos\theta)$$

$$n = (1 - R)/(1 + R - 2\sqrt{R}\cos\theta). \qquad (4)$$

Figure 4 presents that the change in refractive index n and extinction coefficient k of reflective films before and after proton irradiation. The extinction coefficient k reflects the attenuation character of light waves in Al reflective film. On the whole, the extinction coefficient gradually decreases with increasing radiation fluence at a certain wavelength. The results indicate that more light energies enter the metal interior, and this leads to the decrease of the energies of reflective light. As a result, the specular reflectance of reflectors is degraded.

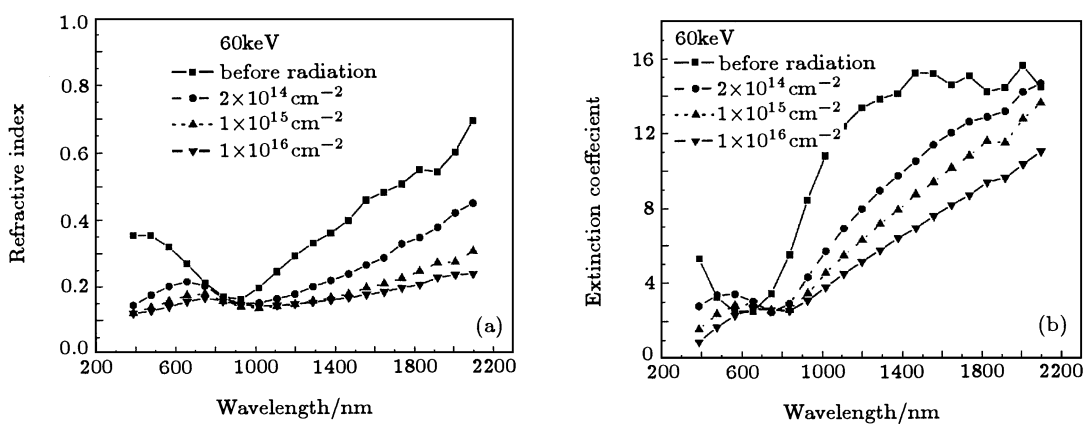


Fig.4. Change in optical constants of the reflective film after 60 keV proton irradiation (a) refractive index; (b) extinction coefficient.

4. Conclusions

This work describes the change in optical constants caused by 60 keV proton irradiation for an Al film reflector. The reflectance spectra and computer simulation show that the degradation in optical property of reflectors can be induced by proton irradiation when the radiation damage is mainly concentrated on the film layers of reflectors. With increasing radiation fluence, the extinction coefficient k decreases, which results in the degradation of specular reflectance of reflectors. Therefore, the degradation in reflectance of optical reflectors under proton exposure with lower energy is an important problem, which must be considered in the longevity design of spacecrafts.

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